BRIDGING DISCIPLINES: THE ROLE OF MATHEMATICAL REASONING IN INTERDISCIPLINARY INQUIRY

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Abstract

This study posits mathematics as a fundamental methodological framework for navigating the complexities of multidisciplinary research. It argues that the increasing prevalence of real-world problems demands the integration of knowledge from diverse scientific fields, where mathematics, particularly through the method of analysis and synthesis, provides a crucial constructive framework. While acknowledging the challenges in applying mathematical proficiency across disciplines and the complexities of interdisciplinary collaboration, the paper highlights mathematics' historical versatility and its role as a "mode of rationality" applicable beyond traditional scientific domains. The topic is explored more broadly and deeply through military technology. The study illustrates the practical application of mathematical reasoning and the inherent value-ladenness of multidisciplinary problem-solving. Ultimately, it concludes that cultivating mathematical literacy and embracing analytical methodologies are essential for fostering effective communication and advancing multidisciplinary research to address pressing global issues.

Keywords: *mathematics education, methodological thinking, multidisciplinary research, scientific reasoning, method of analysis and synthesis*

Introduction

Mature scientific disciplines commonly possess well-defined theoretical foundations and established applications, forming the basis for structured teaching, learning, and research practices. However, contemporary educational research increasingly emphasizes the importance of multidisciplinary approaches. Likewise, real-world problems often require synthesizing knowledge from a wide array of fields. Moreover, seemingly well-defined issues are frequently embedded within practical environments, revealing their multidimensional nature. In such contexts, mathematical knowledge can provide a vital constructive framework.

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https://doi.org/10.33225/BalticSTE/2025.146

Historically, calculus evolved from physics and the natural sciences, but its utility extends far beyond, with notable applications in economics, humanities, and social sciences. Numerous practical projects demand considerable mathematical proficiency. Adams and Essex (2018) offer a compelling example, suggesting that a foundational understanding may require at least a three- to five-semester lecture course. Despite its relevance, such extensive mathematical training is often excluded from curricula due to practical constraints.

Even so, solid mathematical competence remains critical for solving numerous practical problems. While curricula often position calculus as a core component of scientific education, mastering it remains challenging. Completing a calculus sequence does not ensure students can apply it effectively in multidisciplinary contexts. As André Weil's example illustrates, true intellectual creativity requires deep knowledge and adaptable thinking (Weil 1969). The most effective approach cultivates an academic environment promoting systematic study and intellectual engagement across diverse problem domains (Aczel, 2006).

In recent decades, multidisciplinary, interdisciplinary, and transdisciplinary research have become prominent (Frodeman et al., 2017; Hadorn et al., 2008). Nevertheless, these terms still have no universally accepted definition or framework. Practical research and development projects often operate within these paradigms, and philosophical and empirical studies aim to clarify their dynamics (Koskinen, 2014; Koskinen & Mäki, 2016). Addressing global issues—such as climate change, pollution, and overpopulation—demands cross-disciplinary collaboration and participation from experts and the public, ideally beginning from the problem-specification phase (Rissanen & Mutanen, 2019). The categorization of problems into multidisciplinary, interdisciplinary, or transdisciplinary domains does not always clarify how solutions should be pursued. Such projects involve collaboration among varied fields and actors (Klein, 2010). Science education's evolution towards fostering broad scientific literacy parallels these needs. Empowering individuals to understand and engage with science supports the competencies for effective multidisciplinary research (Feinstein et al., 2013; Stuckey et al., 2013).

Solutions to practical problems induce changes in real-world contexts, making these problems inherently value-laden (Balsamo 2017; Funtowicz & Ravetz 2008). Every outcome reshapes the practical environment and the approaches to managing problem situations. Consequently, the full spectrum of consequences remains unknowable in advance. While some outcomes may be anticipated, many significant ones may remain unforeseen. Unfortunately, the reactions to these unknown consequences cannot be predicted, implying that the actual impact of solutions can only be fully understood retrospectively. Fisher and Beltran-del-Rio (2017, p. 114) highlighted "the historical range of mathematics as directly applicable to a wide set of phenomena, practices, and developments in many other fields of learning and human endeavor." Their work broadly illustrates mathematics' constructive role across various scientific disciplines and within culture. Thus, mathematics can be viewed as a methodological foundation for multidisciplinary, interdisciplinary, and transdisciplinary research.

Mathematics has a long history of application in solving practical problems. In antiquity, it was instrumental in astronomical calculations. The primary interpretation was utilitarian. Modern science emerged based on the experimental method, integrating

https://doi.org/10.33225/BalticSTE/2025.146

practical experimentation with the mathematical understanding of experimental data. Furthermore, mathematical modeling could precede case-specific experimentation when appropriate. Key figures in establishing this direction include Galileo Galilei (1564–1642), Isaac Newton (1642–1727), and Gottfried Wilhelm von Leibniz (1646–1716). The mathematical tool they developed, calculus, can be understood as a general problem-solving method (Fisher & Beltran-del-Rio, 2017; Mutanen, 2019).

Viewing mathematics as a general problem-solving methodology compels us to recognize it as a method for conceptualizing and structuring problems. Therefore, mathematics should be understood as a mode of rationality rather than a formal discipline. For instance, Lévi-Strauss employed mathematics to analyze the marriage systems of aboriginal communities (Aczel 2006), underpinning the realism in cubist art (Hintikka 1975; Aczel 2006). In Artificial Intelligence, the challenge of common sense knowledge underscores the importance of analytical reasoning (Copeland 1993; Hofstadter 1999). Consequently, this paper posits that mathematics offers a general methodological framework for rational deliberation, which the method of analysis and synthesis exemplifies (Niiniluoto 2018). The rationale for emphasizing the process of analysis and synthesis stems from the diverse meanings associated with the term "analysis," as Beaney (2021) demonstrates. Therefore, the focus here is to open a discussion on the fundamental human rationality underlying scientific reasoning, which is rooted in the classical method of analysis and synthesis (Mutanen 2019; Lakatos 1976).

Mathematics and Scientific Research

Present-day experimental science is often termed "exact science," a designation that stems from incorporating mathematics (or statistical data) into research reports. However, this label does not fully elucidate the role of mathematics within these sciences, nor its significance in other scientific disciplines. Mathematics holds a central methodological position in both physics and engineering. In English, a more restricted view often equates "science" with the natural sciences, sometimes mathematical or exact sciences. Nevertheless, mathematics, particularly statistics, finds substantial application in fields such as economics and psychology.

Historically, the evolution of mathematics and physics has been deeply intertwined. In physics, a key challenge was to articulate the concept of change, which calculus effectively addresses. The close relationship is evident in the statement: "The acceleration [...] is the rate of change (the derivative) of the velocity, which is in turn the rate of change (the derivative) of the height function" (Adams & Essex 2018, p. 2). Thus, fundamental physics and mathematics (calculus) notions are intrinsically connected. While this connection might become less apparent during a calculus lecture course, it remains a foundational element of calculus theory.

Calculus finds direct application in the natural sciences and engineering. Its development is closely linked to the advancement of physics, providing the logico-conceptual tools necessary to analyze physical phenomena. A core concept like instantaneous velocity relies on the possibility of considering progressively smaller time intervals and displacements, whose logico-mathematical analysis hinges on the notion of a limit. Extending this process indefinitely leads to the concept of infinitesimals (Boyer 1949). However, despite its historical roots in physics, calculus also has significant

https://doi.org/10.33225/BalticSTE/2025.146

applications in the human sciences (Barnett 2019). This broad applicability arises because calculus solves specific problems regardless of their subject matter. Indeed, calculus textbooks often share similar content, whether intended for natural scientists or those in the humanities.

Mathematics extends far beyond calculus, encompassing a vast and intricate landscape. For instance, Glymour and Cooper (1999) demonstrated the applicability of Bayesian networks across diverse contexts. The Bayesian approach is integral to statistical or probabilistic reasoning, which enjoys widespread use in various scientific fields (Suppes 1969). Bayesian networks are a component of the more general graph theory (Bondy & Murty, 2008), providing a broader framework. Furthermore, in social sciences and economics, game theory (von Neumann & Morgenstern 1944) has numerous applications, such as in decision theory (Raiffa 1970), where mathematical analysis reveals paradoxes inherent in the structure of specific complex decision problems (Campbell & Sowden 1985). Such examples deeply characterize human nature, as preference theory (with its mathematical-logical structure) demonstrates (von Wright 1983). More generally, mathematics is not merely a quantitative or qualitative research tool but a more encompassing methodological discipline that supports all rational human endeavors, such that "not a single area of human interest would be left untouched" (Aczel 2006, p. 57).

While emphasizing the role of mathematics as a methodological tool, it is crucial not to overlook that in scientific research, (applied) methods are not simply instruments. Methods and content engage in a mutual interplay that must be considered from the initial research planning stages. This interaction is also evident in textbooks. For example, Cutnell and Johnson (2005) stressed the importance of "conceptual understanding and problem solving" in physics. Simultaneously, they noted that "physics is often regarded as a collection of equations that can be used blindly to solve problems." What else could calculation-based problem-solving in physics entail? Calculus can be employed as a content-neutral problem-solving mechanism: if a problem exhibits a specific structure, it can be formalized and solved by mechanically applying particular calculations.

Scientific reasoning transcends mere formal rationale; it is inherently contentful. It involves analyzing the problem situation, particularly the phenomenon under investigation. The mathematical representation of physics offers readily available formal solutions. However, relying solely on calculation is insufficient. Unfortunately, homework exercises solvable by direct formula application often provide limited insight into genuine scientific problem-solving. They might be more accurately characterized as quasi-practical problems. In actual practical issues, the initial step involves a thorough analysis of the phenomenon under study, which can be a research-like undertaking (Hintikka & Remes, 1974).

The overall planning of scientific research constitutes part of the methodology. Methodology mathematics is not a specific branch of mathematics but rather a general orientation of scientific rationality. Within a method, the fundamental task is to situate the problem within an intellectual framework. Typically, problems are not well-defined initially, and the primary challenge is to identify the relevant aspects of the problem and determine how they can be addressed. Only after this initial localization can the proper scientific problem specification begin.

https://doi.org/10.33225/BalticSTE/2025.146

The Method of Analysis and Synthesis

The study of mathematics education has shown considerable interest in mathematical reasoning – the processes involved in reasoning mathematically. The concept of mathematical reasoning is linked to mathematical formalism, as Turing (1939) explicated. Furthermore, Turing (1939, 208-209) discussed the roles of intuition and ingenuity in mathematics. Intuition, in this context, "consists in making spontaneous judgments which are not the result of conscious trains of reasoning." Generally, intuition is often viewed as an alternative to rational reasoning. However, intuition has played a more constructive role in the philosophy of logic and mathematics, as Kant articulated (Hintikka & Remes 1974; Niiniluoto 2018; de Toffoli 2019).

According to Turing (1939, p. 209), "ingenuity in mathematics consists in aiding the intuition through suitable arrangements of propositions, and perhaps geometrical figures or drawings," intended to demonstrate the validity of intuitive reasoning. The foundation of this kind of ingenuity has also been extensively studied in the philosophy of logic (Mumma, 2012). Creativity and intuition have been examined more recently in mathematics education (Kontorovich & Liljedahl, 2018). In education, the focus has often been on empirical aspects of learning, such as psychological or sociological factors, rather than the logico-conceptual aspects of learning mathematics. However, this distinction should not be overstated, as there are apparent structural similarities between the work of Liljedahl (2018) and Jung (1996), although the latter emphasizes methodological aspects. This paper aims to briefly explore the foundations of mathematics, a topic extensively investigated in logic (Jaquette 2002).

For today's education researchers, this paper aims to observe, discuss, and refresh the classical method of analysis and synthesis. The method originated in ancient geometry. In this tradition, the search for proofs of theorems was termed theoretical analysis, while the search for constructions to solve problems was called problematical analysis (Hintikka & Remes 1974). School mathematics commonly illustrates the creative nature of geometrical reasoning. Furthermore, diagrams play a significant role in geometrical reasoning, making it practical. In a geometrical proof, "it seldom suffices to consider the given figure, i.e., the figure of which the antecedent of the proposition speaks" (Hintikka 1973, p. 202). Instead, we require "a 'preparation' or a 'construction' or a 'machinery'" (ibid.) – additional information that completes the proof. Such a method of analysis can be termed constructional analysis (Hintikka 1973, p. 201). Descartes generalized the analysis method from analyzing geometrical figures to analyzing algebraic equations (Mutanen 2019).

Learning objectives have widely been discussed in educational science, with Bloom's taxonomy (Agarwal 2019) serving as a key reference point. Bloom's taxonomy aims to characterize the depth of learning by referring to the hierarchical steps within the taxonomy. This paper focuses on the mathematical structure of the topic, shifting attention from the learner's pure taxonomical state to the logico-conceptual structure of the subject matter. Fortunately, there is a significant interconnection between the two: a deeper level of analysis (in the logical sense) corresponds to a deeper understanding of the original meaning of Bloom's taxonomy. The logico-conceptual approach presented in this study can be applied to analyze the pedagogical approach developed by science education researchers Kokkonen and Mäntylä (2018).

https://doi.org/10.33225/BalticSTE/2025.146

The grand method of analysis and synthesis has not been confined to mathematical reasoning: "Newton – probably the most famous admirer of ancient Greek geometry – assimilated in so many words his experimental method to 'the Method of Analysis'" (Hintikka & Remes 1974, p. 1). The situation is analogous in scientific analysis, but the subject of study is externally given. It is a mathematical fact that no universal method exists for finding the best constructions in geometry, implying that geometrical reasoning is inherently creative (Hintikka 1973, p. 203). The situation in physics is structurally similar, even though physics addresses factual matters in a well-established manner.

Thus, analysis is a research-like process. Constructing the experimental setup in experimental physics corresponds to creating an analytical geometrical proof. However, just as in geometry, the theoretical background knowledge guides the construction of the experimental setup. Unfortunately, there is no guarantee that optimal construction will be achieved. There are two primary reasons for this. Firstly, the practical reason is the theoretical challenge of identifying the most fundamental questions (parameters) in an experimental situation. Secondly, the theoretical reason is that there are no assurances that the analysis can be completed.

Developers of educational materials must acknowledge the inevitability of misconceptions among learners, even with thoroughly tested materials. However, these misconceptions can serve as a valuable foundation for clarifying discussions and knowledge formation. Logical reasoning and its specific manifestations are essential to exercises and problem-solving in education. Many problems (e.g., in physics) can be solved using nonstandard methods or intuition (Belikov 1986). Nevertheless, standard methods typically yield more systematic results. Therefore, students must develop the ability to analyze (physical) phenomena and understand how to formulate a standard approach to solutions. Moreover, exercises aim to foster students' creative thinking (Sena 1988). The rote repetition of relatively simple mathematical tasks embedded in a superficial context may create a false sense of acquired skills. Conversely, tasks that are overly demanding and lack sufficient support may obscure the practical significance of calculus. Consequently, the type and number of similar exercises need to be carefully adjusted to the knowledge level of the student group and the available resources for practice.

Multidisciplinary Research in Military Education

In multidisciplinary research endeavors, the complexity of the situation can be considerable. For instance, global warming exhibits extreme multiplicity, challenging the identification of foundational facts due to the measurement procedures' theory-laden nature. Furthermore, even the designation of field experts can be contentious (Lindzen 2017). Addressing global warming necessitates knowledge integration from diverse scientific domains, expertise from various practical fields, and the application of new or emerging technologies. Consequently, solutions are invariably intricate amalgams of knowledge, skills, and values derived from disparate sources (Balsimo 2017).

To render the discussion more manageable, we will consider a more circumscribed case: military technology. This example illuminates several intriguing facets of multidisciplinary research. Military technology represents a domain of expertise that intricately connects technology, planning, leadership, and education. Moreover, proactive efforts are often made to incorporate user experiences during the planning

https://doi.org/10.33225/BalticSTE/2025.146

phase within military technology, which characterizes military technology projects as transdisciplinary.

Let's undertake a concise philosophical analysis of military technology projects. Historically, military technology has been considered a leading edge area of expertise and developmental aims. While technology has sometimes been described as applied science, Dusek (2006, p. 33) correctly points out that this represents only a partial truth at best. Fundamentally, science is categorized as basic science, defined as "the systematic pursuit of new scientific knowledge without the aim of specific practical application" (Niiniluoto 1993, p. 2). In contrast, applied science is "the pursuit of knowledge to obtain a specific goal" (ibid.). Technology, however, is not merely such a pursuit but rather an integral component of development, which seeks "new products, methods, and means of production" (ibid.) based on the findings of both basic and applied sciences.

It is instructive to delineate different research approaches based on the fundamental utilities they prioritize. In this context, basic science is fundamentally an epistemic endeavor, where epistemic utility constitutes the paramount value or utility. The primary objective is the acquisition of novel knowledge about reality. While epistemic utilities are also present in applied science, these endeavors concurrently aim for various forms of practical utility. Applied science thus seeks not only truthful knowledge but also tangible benefits. In the realm of technology, and more broadly in development, the emphasis shifts firmly towards practical utilities (Niiniluoto 1993), with knowledge primarily holding instrumental value. Indeed, members of the Frankfurt School extended this perspective to encompass all scientific endeavors (Dusek 2006). In military technology education, an initial, concise review of mathematics and physics at the high school curriculum level is often undertaken to provide practical analytical tools for examining complex phenomena. Consequently, successful military technology represents a synthesis of science-based technology, military leadership, and military pedagogy. The requisite mathematics for studying each element includes calculus, game theory, and graph theory. While mastery at a professional level falls outside the scope, the aim is to cultivate thinking and analytical proficiency for future engagement with unforeseen problems.

The Origin of Logic in Technology

Technology, particularly contemporary high technology, is in some sense science-based. However, precisely delineating the relationship between science and technology can be challenging. Significant technological development still occurs without a discernible connection to scientific knowledge. To analyze this relationship more closely, let us consider the technical norm articulated by Georg Henrik von Wright and formulated by Niiniluoto (1993):

Technical norm: If you want A, and believe you are in a situation B, then you should do X.

That is, technical norms express "technical oughts" that are only binding if the antecedent conditions are accepted – if one adopts A as a desired goal and believes the current situation to be B.

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Technical norms rest on the assumption that X is feasible, which necessitates that the technology is, to a significant extent, under the agent's control. This can be termed the manipulativity condition. Furthermore, the agent believes that, in situation B, X causally leads to A. This causal relationship is fundamentally a product of experimental science. For instance, in the context of global warming, there is an underlying assumption that the international atmosphere is manipulable by human actions. Indeed, a substantial body of scientific knowledge demonstrates how human behavior has altered the climate.

The technical norm highlights the inherent value-laden nature of technology. Values are explicitly articulated within technical norms. However, a more in-depth analysis of the values underpinning these norms requires further investigation in each specific case. The preceding characterization reveals that analyzing a technological problem necessitates knowledge from diverse, case-specific fields of expertise. We have already mentioned scientific knowledge, which can be drawn from various scientific disciplines depending on the technological problem. Given that military technology is typically deployed in extreme situations, its study inherently involves multiple scientific fields, as previously noted. The other domain of expertise mentioned was ethics (values). How can values be integrated into the solution of a technological problem? Is it sufficient for the final decision-making process to take them into account?

Bunge (2006, p. 178) characterized technological problems as frequently being reverse engineering problems that "are typically design or maintenance problems." Technology has been classified as part of the so-called design sciences (Simon 1968; Niiniluoto 1993; Galle & Kroes 2014). Design is an activity initiated by a preliminary concept of a desired outcome, often with imprecisely defined goals and constraints that must be satisfied. These constraints can be diverse, encompassing factors such as final cost, materials employed, or practical usability. Even within the often chaotic and knowledge-deficient context of military operations, a significant body of general knowledge adequately specifies usability constraints. For example, these constraints might define the extreme conditions under which the technology-human system must function effectively.

The design process serves as an excellent illustration of the method of analysis previously characterized. Design might commence with the envisioned end product that meets all specified constraints. The study then progressively delves into the product's structure, elaborating on increasingly finer details until all relevant aspects are defined. Upon completion of the analysis, explicit knowledge regarding the product's construction, required materials, and inherent properties is obtained. Naturally, depending on the imposed constraints, all potential side effects will also have been elucidated. Before commencing production, all the knowledge and details about the construction process must be thoroughly evaluated. For the described task here, military technology education projects provide valuable examples where different facets of the planning process can be exercised in multidisciplinary ways.

Discussion

This exploration has underscored mathematics' indispensable role as a foundational methodology for navigating multidisciplinary research complexities. The increasing prevalence of real-world problems transcending disciplinary boundaries necessitates

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knowledge integration, where mathematics, provides a framework for conceptualizing intricate scenarios. Recognizing that mathematical mastery doesn't automatically ensure practical multidisciplinary application highlights the need for intellectual flexibility and environments fostering systematic study. (Aczel 2006.) The prominence of multidisciplinary, interdisciplinary, and transdisciplinary research, driven by global challenges, further emphasizes the need for frameworks bridging disciplinary divides. While definitions and approaches vary, practical knowledge integration and diverse expertise are crucial (Rissanen & Mutanen, 2019). The inherent value-laden nature of real-world solutions (Balsamo 2017; Funtowicz & Ravetz 2008) adds complexity, demanding consideration of non-obvious consequences. Analyzing mathematics as a methodological tool beyond computation reveals its capacity as a "mode of rationality" (Niiniluoto 2018). Its application in diverse fields illustrates its power in structuring complex systems. Emphasizing analysis and synthesis, rooted in geometry and adopted by scientific pioneers (Hintikka & Remes 1974), highlights a fundamental problem-solving approach in mathematical and scientific reasoning. Exploring mathematical logic, including intuition and ingenuity (Turing 1939), enriches understanding of complex problem-solving.

The military technology and its education offer a multidisciplinary field integrating technology, planning, leadership, and education. Applying the "technical norm" (Niiniluoto 1993) reveals the value-ladenness of technological development and the need for ethical considerations alongside scientific and practical aspects. The design process in military technology exemplifies analysis, moving from desired outcomes to detailed specifications. Unifying languages and theories across disciplines in multidisciplinary research is challenging (Tuomela 1973; Niiniluoto & Tuomela 1973; Stegmüller 1976). While examples like physical chemistry exist, many situations require navigating distinct conceptual landscapes. Without universal solutions, respectful dialogue and effective communication are paramount (Heinonen 2017), highlighting the importance of mathematical reasoning in facilitating this and fostering science literacy.

Conclusions

This study explores the methodological advantages of mathematics in tackling complex challenges, particularly in structuring research and addressing logically defined tasks. A perspective on broad applicability and connection to scientific reasoning is presented through analysis and synthesis. The mathematical-logical examination emphasizes the method's ability to provide a unifying framework for diverse research. The complexities of integrating knowledge, particularly in terms of unifying languages and theories, necessitate a focus in research activities on promoting communication and shared analytical approaches. Ultimately, developing mathematical literacy and embracing analysis and synthesis are crucial for advancing effective multidisciplinary research and solving global problems.

https://doi.org/10.33225/BalticSTE/2025.146

Acknowledgements

The authors thank colleagues and mentors for valuable insights, faculty and researchers in mathematics education and philosophy of science for enriching discussions, reviewers for constructive comments, and the institutions for research support.

Declaration of Interest

The authors declare no competing interest.

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Received: *April 05, 2025* Accepted: *May 20, 2025*

Cite as: Mutanen, A., Rissanen, A., & Saastamoinen, K. (2025). Bridging disciplines: The role of mathematical reasoning in interdisciplinary inquiry. In. V. Lamanauskas (Ed.), *Science and technology education: Expectations and Experiences. Proceedings of the 6th International Baltic Symposium on Science and Technology Education (BalticSTE2025)* (pp. 146–157). Scientia Socialis Press. https://doi.org/10.33225/BalticSTE/2025.146